N72-12600

NASA TECHNICAL MEMORANDUM

NASA TM X-67958

NASA TM X-67958

CASE FILE COPY

MINI GAS-CORE PROPULSION CONCEPT

by Robert E. Hyland
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER presented at Winter
Meeting of the American Nuclear Society
Miami, Florida, October 17-21, 1971

E-6665

ABSTRACT

A propulsion concept is presented that can achieve specific impulses of 1000 to 2000 seconds for thrust levels on the order of 100 pounds (445 N) and maintain a small (1.22 m) reactor diameter for a total powerplant weight of approximately 10 000 kg. The concept combines a small (0.61 m) diameter spherical gas core centrally located, followed by a moderator (BeO-15 cm), surrounded by a driver fuel region and contained in a pressure vessel (ID of 1.22 m). Best results (i.e., highest ratio of cavity power to total power) occur with ^{233}U isotope as the fuel in both the cavity and the driver, although ^{235}U can also be used. Concept may also have application in the testing of a gas-core reactor and MHD devices and in high temperature-pressure materials research.

MINI GAS-CORE PROPULSION CONCEPT

by Robert E. Hyland

Lewis Research Center

E-6665

SUMMARY

A propulsion concept to obtain high specific impulse (approx. 1000-2000 sec) while maintaining a lightweight reactor is analytically investigated. The concept called the mini-cavity combines a small spherical (0.61 m) diameter cavity for heating the hydrogen propellant with a surrounding moderator (BeO) and driver fuel region, all located inside of a pressure vessel.

In the report the cavity and the overall diameter of the reactor are fixed at 0.61 and 1.22 m, respectively. The variables in the calculations are the moderator thickness between the cavity and the driver fuel, the use of uranium isotopes 233 or 235, the moderator within the driver fuel, and the thickness of the pressure shell (iron) surrounding the reactor. As a result of the analyses a BeO thickness of 15 cm between the driver region and the cavity was selected as the best thickness and the effect of the pressure shell on the outside was to increase the reactivity and thus allow a reduction in driver fuel density which in turn raised the power fraction of the cavity. With high power fractions in the cavity the radiator required to dump waste heat from the driver region is reduced in size and weight. In addition a typical powerplant is presented which would produce a thrust of 450 newtons at a chamber pressure of 500 atmospheres, with a specific impulse of 1600 seconds and a weight of approximately 10 230 kg including the weight of a radiator to dispose of the power produced in the driver fuel region.

The author concludes that not only does the concept lend itself as a propulsion system for high specific impulse with relatively low weight, but it also may have application as a testing reactor for the gas-core and MHD devices and for materials work at high temperature and pressure.

As a propulsion concept the selection of ^{233}U as the fuel for both the cavity and the driver fuel greatly enhances the system because it lowers the fuel inventory in the driver fuel region which results in a higher ratio of cavity power to total power (>20%).

INTRODUCTION

There appear to be many probe type missions that would be enhanced if higher specific impulse were available without sacrificing thrust to weight ratios. The solid core nuclear reactor such as NERVA offers an increase from 400 second range for chemical propulsion to 800-900 second range. The limits here are due to the limiting temperature on materials and operational time. If a gas-core reactor were used instead of a solid core reactor, the powerplant would be too heavy for deep probe missions requiring low power levels. However, it may be possible to combine the solid core reactor with the gas core and add sufficient impulse without paying a weight penalty and operate in the low thrust region around 100 pounds (450 N).

This paper attempts to show that neutronically it is possible to merge the two reactor concepts into a single compact lightweight reactor capable of a thrust level of 450 newtons (100 lb) with an impulse of at least double that of solid core reactors.

The idea of combining the solid core reactor with a gas core is pursued in this paper by attempting to maximize the power of the gas core relative to the solid core and thereby minimizing total power and powerplant weight. The minimum goal was 10 percent power in the gas core region with a powerplant weight of approximately 10 000 kilograms.

The question as to whether a reactor of this type could be made and operated would place the burden on the gas-core portion since the solid-core reactor has been demonstrated in many test runs. One of the earlier problems of the graphite-uranium core based on NERVA research was in the use of hydrogen as a propellant. In the mini-gas core concept the driver region is not used to heat the propellant so that a more compatible coolant such as helium or argon (ref. 1) can be used.

As for the gas-core portion, experiments in the areas of high temperature plasma, hydrodynamic flow, absorption of radiant energy by seeded gases, and neutronics have been conducted. High temperature plasmas (>10 000 K) have been obtained in reference 2. Volume fractions of gases representing fuel to total cavity volume in the range of interest (0.2-0.3) have been obtained (refs. 3 and 4). Seeding the propellant gas to pick up the radiant energy has been successful (ref. 5). Neutronic critical experiments have produced data on criticality, reactivity worth of materials, power distribution, and control characteristics and have demonstrated that uranium gases (UF_6) can be used and controlled (refs. 6 to 8).

The question as to controllability may arise in a gas-core reactor because of fuel motion, but with the driver region in this concept being a solid fuel, control can more readily be achieved in the moderator region between the two fueled regions. This therefore uses some of the best features of solid and gas core concepts, i.e., controllability with the solid fuel driver and the high specific impulse of the gas core.

APPROACH

Reactor Configuration

In order to keep the reactor weight low a spherical cavity diameter of 60.48 centimeter was selected for analysis. Surrounding this was a moderator region for the cavity to supply thermal neutrons to the cavity fuel as shown in figure 1. Outside of this was the main fuel region or driver fuel for the concept. Because of the pressure necessary for the cavity gas, a pressure vessel was added on the exterior as shown in figure 1. Since the pressure shell would absorb thermal neutrons, it was necessary to place it outside of the driver fuel.

In the gas-core, the fuel occupied the central portion with a radius ratio of 0.70 of the cavity. The fuel was uranium in a gaseous state and both ^{233}U and ^{235}U isotopes were used. Hydrogen was selected as the propellant. Its density was varied between 1.2×10^{20} and 4×10^{21} atms/cc.

Surrounding the spherical cavity was a thick region of beryllium oxide (BeO) to moderate fast neutrons from the driver region (solid core) and to reflect thermal neutrons into the gas core.

The next region contained the driver fuel region. The fuel selected for this region was uranium dispersed in graphite. Again, both uranium isotopes (233 and 235) were tried. It was this region that was varied in thickness, density and position in an effort to provide sufficient reactivity for a critical reactor and provide a supply of neutrons to the gaseous central core. These neutrons were thermalized by the BeO region between the gas and solid fuel regions. The two basic arrangements for driver fuel (i.e., single fuel region and double fuel region with moderator between) are presented in figure 2.

Outside of the solid fueled region, or driver region, was a thin thermal reflector of BeO and a pressure vessel. The pressure vessel is necessary for containing the high pressure in the cavity for the various fuel and hydrogen densities. The vessel was placed on the outside to reduce its absorption of thermal neutrons. As will be discussed under results it becomes a good high energy neutron reflector. By placing the pressure vessel outside of the driver fuel the coolant for the driver can be a gas at high pressure. This high pressure coolant gas can be used in a loop with an intermediate heat exchanger with a low pressure coolant on the secondary side or it can be used directly with a high pressure radiator. The latter approach was selected in this analysis.

Computer Program and Cross Sections

The analysis was performed with a transport code, reference 9, called TDSN. The code was run for a discrete angular segmentation (S_n) of S_4. The microscopic cross sections were obtained from data tapes and programs, GAM II for fast and intermediate energies and GATHER II for thermal energies. The energy range was divided into 19 groups as shown in table I. The microscopic cross sections in the thermal range for the driver region were averaged over a flux obtained by using the B_1 approximation to the static Boltzmann transport equation. The average temperature for the hydrogen in the gas core was assumed to be 6400° C and had an atom density of 1.2×10^{20} atoms/cc.

Analytical Approach

As was pointed out in the INTRODUCTION it is desirable to maximize the ratio of cavity to total power. For a given power in the cavity the driver power is thereby minimized. Since the driver power is dumped via a radiator, the total powerplant weight is minimized. The approach used was to select various masses of fuel in the cavity in the range of interest and then vary the moderator, driver region, and reflectors in such a manner, as will be discussed, to maximize the relative power in the cavity. This will be referred to as the power split.

ANALYSES

Cavity Fuel Density Selection

From previous calculations of gas-core reactors, a relationship involving the amount of fuel in a cavity, the size of the cavity, the reactor pressure, the fuel volume fraction of the cavity, the thrust and specific impulse was derived (ref. 10). That relationship is expressed in equation (1).

$$M_F = 10.7 \frac{D_C^{3.28}\, P^{0.723}\, V_F^{1.092}}{F^{0.277}\, I_{sp}^{0.277}} \tag{1}$$

With a consistent set of values for the thrust, specific impulse and pressure, the allowed fuel in the cavity, M_F in kilograms, can be obtained. In equation (1), D_C the cavity diameter is in meters, P the chamber pressure is in atmospheres, the thrust, F, is in newtons, and the I_{sp} impulse is in seconds. V_F is the volume fraction occupied by fuel. A consistent set of engine characteristics (thrust, pressure, impulse) are presented in figure 3. These values were obtained from an analysis similar to that used in reference 11. The purpose here is merely to indicate the fuel mass that can be reasonably assumed in the cavity. Using values from figure 3, a cavity diameter of 0.61 meter, and a fuel volume fraction of 0.30, the allowable fuel mass for the cavity was obtained and is shown in figure 4. For the purpose of analysis in this report, a uranium mass in the cavity between 0.5 and 2.0 kilograms was used. In the analyses the reactors were made critical by varying the amount of fuel in the driver region for a fixed amount in the cavity.

Moderator Thickness

In order to achieve a thermal neutron spectrum in the cavity fuel a good moderator between the driver fuel and the cavity is required. For high temperature operation BeO was selected. The moderation is a function of the BeO thickness as well as its ability to slow neutrons down by collision. Therefore in order to maximize the flow of thermal neutrons into the cavity and thus maximize the power in that region, the thickness of BeO was varied between 10.16 and 20.32 centimeters. Since the reactor diameter was maintained at 122 centimeters, the BeO region between the driver fuel and the pressure vessel was also varied when the BeO moderator surrounding the gas core was varied.

The Driver Fuel Region

The solid fueled portion of the reactor was assumed to be uranium mixed with graphite, similar to that used in the NERVA program. The uranium content was varied from 100 to 1000 milligrams per cubic centimeter of graphite. In the fuel region a void allowance of 20 percent was made for coolant (i.e., a spacing of 0.063 cm between fuel plates of 0.254 cm). No coating was assumed for the graphite since it would be possible to use an inert gas for transferring thermal energy from the driver region to a radiator.

In the analysis the driver region was varied both in position relative to moderator and in thickness. The driver region was considered as both a one fuel zone and as two fuel zones (fig. 2) with BeO (2.54 and 5.08 cm thick) between.

Weight Analyses

Reactor weight: Using a consistent set of values for thrust, pressure, and specific impulse the amount of fuel in the cavity could be obtained through equation (1) from reference 10. This amount of fuel in the cavity coupled with the proper amount in the driver region constituted a critical reactor for various thicknesses of moderator and pressure vessel. From this, the size and weight for the reactor could be obtained.

Pressure vessel weight: The pressure selected for each case can be related to a pressure vessel thickness by

$$t = \frac{PR}{2S}$$

where P is the chamber pressure, R the radius of the sphere, and S, the allowable stress. By selecting an iron base alloy and a temperature, the thickness of the pressure vessel and hence its weight can be determined.

Radiator weight: If a graphite fuel element such as those developed under NERVA program were used with an inert gas, the heat deposited in that region would be rejected through a radiator. The radiator weight is an important part of the total powerplant weight and must be incorporated with at least a good estimate. Based on results of reference 12, a weight of 310 kg (684 lb) per megawatt was chosen as representative of a type of radiator that could be used for this application (i.e., high temperature and pressure).

RESULTS

The results of the neutronic analysis are discussed on the basis of the power split between the cavity and the driver region. The power splits is a function of the uranium isotope (^{233}U or ^{235}U), the moderator thickness, the outer reflector thickness, and the pressure shell thickness.

The use of uranium isotopes (^{235}U or ^{233}U) in either the cavity and/or the driver are considered. The main concern for the mini-cavity concept is to keep the total weight low while maintaining a high outlet temperature in the cavity. Since the weight is strongly influenced by the radiator weight, the power in the driver region should be minimized for a given pressure level.

Effect of Uranium Isotopes (233 and 235) in Cavity

Using model (a) of figure 2 (two fuel zones), a thickness of 2.54 centimeters for each driver fuel zone, one kilogram of uranium (233 or 235) in the cavity and a moderator (BeO) thickness (15.24 cm) between the cavity and the driver, calculations were performed for each isotope. With ^{235}U in the cavity and in the driver, the power in the cavity is less than 0.10 of the total reactor power. When the ^{233}U isotope is used in the cavity, this power fraction increased to 0.135. This indicated that the use of ^{233}U would increase the power in the cavity relative to that in the driver. The next step was to determine how a similar change in the driver fuel would effect the power split.

Effect of Uranium Isotopes (233 and 235) in Driver Fuel

Again, using model (a) as above with the same dimensions, a comparison between ^{233}U and ^{235}U in the driver fuel was made. For this comparison, 1 kg of ^{233}U was in the cavity. With uranium-235 as the driver fuel a critical configuration with 106 kg in the driver region resulted in a relative power fraction of 0.135 in the cavity as indicated in the above paragraph. When the uranium-235 in the driver region was replaced with uranium-233, the driver fuel mass had to be reduced to keep the reactor critical. The driver fuel was reduced to 23 kg of uranium-233. With this reduction in fuel the power split or relative power fraction in the cavity is increased to 0.158.

Although both values (0.135 and 0.158) are acceptable, the gain in the relative power fraction using all ^{233}U can contribute to reducing the weight of the powerplant and also in reducing the amount of fuel required.

The relative fluxes are plotted in figure 5 for both uranium isotopes in the driver fuel. These curves show the thermal flux for the cavity with ^{233}U as the driver fuel. The two flux levels plotted are the dominate flux energies for fast and thermal. The mean energy for fission absorption in the cavity is in the energy range between 0.12 and 0.08 eV while the mean energy in the driver is in the group between 0.414 and 0.2 eV for ^{233}U and between 61 and 8.3 eV for ^{235}U.

Since the concept is predominately a thermal reactor it is necessary to obtain high thermal flux in the cavity. Figure 5 indicates that the thermal flux was approximately 10% higher in the cavity for the all ^{233}U versus the ^{235}U in the driver. Note that when the density or mass of driver fuel decreased for ^{233}U, the thermal flux increased thus reducing the possible benefit in power split.

Effect of Moderator Thickness

Since the gas-core concept as proposed here requires thermal neutrons to be effective, a thick moderator between the driver fuel and the cavity is important.

To investigate this effect the geometry in figure 2(b) with a driver fuel region thickness of 5.08 centimeters was selected. With the cavity dimensions and the reactor diameter fixed the thickness of the BeO between the cavity and the driver fuel was varied. The thickness was varied between 10.16 and 20.32 centimeters. At the same time the BeO reflector outside of the driver region was varied. The power splits for the cavity for these cases are plotted in figure 6. The maximum power fraction was obtained for a thickness of 15 centimeters of BeO moderator. This was then selected as the thickness for the remaining calculations.

In comparing model (a) with model (b) of figure 2, the BeO between the two driver fuel zones of (a) was moved to the outside of the reactor. The resulting power fractions differed by less than 0.005 and favored the single fuel zone.

In order to determine the effect on reactivity of variable hydrogen density in the cavity region, a calculation was performed with ^{233}U as fuel in the cavity and in the driver where the hydrogen density in the cavity was varied by a factor of 33. The hydrogen density was increased from 1.2×10^{20} to 4.0×10^{21} atoms/cc to reflect a large change in cavity pressure. This large change resulted in a reduction in the effective multiplication factor K from 1.026 to 1.011 or about 1.5%. The hydrogen density of 1.2×10^{20} atoms/cc was representative of the chamber pressure less than 100 atmospheres while the 4.0×10^{21} atoms/cc represented chamber pressures greater than 1000 atmospheres. The effect of hydrogen density on reactivity therefore would be approximately one percent $\Delta K/K$. Since the hydrogen effect was small, it was not considered as a variable in the remaining calculations and a hydrogen density of 1.2×10^{20} atoms/cc was held constant.

Effect of a Pressure Vessel on the Cavity Power Fraction

In the gas-core concept a high pressure cavity is a necessity for density and temperature levels. It can also be shown that any nonproductive absorption of neutrons near the cavity results in a large penalty in either the critical mass for a gas-core reactor or in the case of the mini-cavity a penalty in the power split. For this reason the pressure vessel must be removed from the vicinity of the cavity. In this concept it was placed outside of the driver region. Fortunately with the driver region located near the exterior of the reactor the pressure vessel acts as a fast neutron reflector.

Three thicknesses (2.54, 7.62, and 12.7 cm) of iron were placed next to the outer BeO region as shown in figure 2(a). In each case the reactivity increased so that the fuel loading in the driver region could be reduced and thus improve the cavity power fraction. A set of curves showing power fractions as a function of mass of ^{233}U in the cavity for each of the above thicknesses of pressure shell is shown in figure 7. Of all the effects discussed in this report the effect of the pressure shell was the most significant. As an example, for a given mass in the cavity of one kilogram the power fraction increases from 0.158 to 0.21 for an increase in pressure shell thickness of from 2.54 to 12.7 cm. This effect reflects the fact that a large fraction of neutrons were leaking from the driver fuel region. By reflecting them back into the driver region and the moderator, a higher reactivity resulted. This increase in reactivity resulted in a reduction of the fuel loading in the driver and thereby improving the power split for the cavity.

Typical Powerplant Conditions

For this concept a low thrust level in the range of 20 to 200 pounds (89 to 890 N) with a chamber pressure in the range of 200 to 1000 atmospheres may result in lightweight powerplants which are light enough to be carried in the shuttle rockets. The following data represents a consistent set of numbers for a typical mini-cavity reactor. For a pressure of 500 atmospheres and a thrust level of 100 pounds (445 N) a specific impulse of 1600 seconds is obtainable from a gas-core based on preliminary analyses. Using these values, a cavity diameter of 0.61 meter and a volume fraction of fuel in the cavity of 0.30, the mass of fuel in the cavity can be obtained from equation (1) or figures 3 and 4. This results in 1.42 kg of fuel in the cavity. The enthalpy deposited in the hydrogen propellant to obtain the impulse can be related to the power in the uranium fuel, reference 10. For this case a power of 4.5 megawatts was calculated for the uranium in the cavity. Figure 7 indicates that for the 1.42 kg of ^{233}U in the cavity and a 7.62 cm thick pressure vessel for 500 atmospheres (design stress, S, of 30 600 psi) the power fraction for the cavity is 0.22. Therefore, the power in the driver region is 15.9 megawatts. The average thermal ($E < 0.414$ eV) flux in the cavity for this case is approximately 2×10^{14} neutrons/cm^2-sec.

The weight of the reactor for a spherical diameter of 1.22 meters is approximately 2200 kg. The pressure shell is 7.62 cm thick with an inner diameter of 1.22 meters and a density of 7.6 g/cc (iron) and weighs approximately 3100 kg. This weight could be reduced with a better material but altering material may influence the weight of the radiator through the reflectivity of neutrons back into the reactor and thus changing the driver power.

An estimate of radiator weight can be obtained using the results from reference 12. In that reference an inert gas could be used in the radiator. The temperature for the radiator was 940 K. The radiator was a finned tube array with the fins between tubes on a center to center basis. The fins and tubes were of beryllium. An allowance of one half the tube thickness required for pressure was added for meteoroid protection. A radiator weight per megawatt of power radiated of 310 kg was selected. For 15.9 megawatts the radiator would weigh approximately 4930 kg. Therefore, the total weight of the powerplant including reactor, pressure shell, and radiator would be approximately 10 230 kg. It would deliver a thrust of 445 newtons (100 lb) with an impulse of 1600 seconds.

Other Potential Applications

One of the problems facing the development of a full-scale gas-core reactor is that of testing one. The mini-cavity, although it cannot answer all the questions on the gas core, can be used as a testing facility for such items as injection of both fuel and propellant, cavity wall materials, effect of seed in the hydrogen propellant, effect of fission heating, and radiant heat transfer on fluid mechanical behavior, nozzle configurations and cooling, and provide assistance in studying methods for controlling the reactor power and reactivity. In addition the exit gas temperatures are in the range (4000 to 5000 K) for making MHD devices highly efficient. Because of the high pressures and temperatures the concept may also have application in materials research.

CONCLUSIONS

A concept to obtain some of the impulse potential of a gas-core reactor while maintaining the compactness and light weight of the NERVA reactor was presented. It is concluded that a reactor 1.22 meters in diameter with a cavity diameter of 0.61 meter can be made critical and produce sufficient power (power fraction 0.22) in the cavity fuel to develop thrusts on the order of 100 pounds (450 N) at a chamber pressure of 500 atmospheres with specific impulses at least double that for solid core reactors. For the mini-cavity reactor powerplant presented, the weight estimate for the reactor, pressure shell, and radiator for the above size, pressure, and thrust level was 10 230 kg.

Other conclusions based on the results presented are as follows:

1. There is an optimum thickness of moderator between the cavity and the driver region. For the size and geometry arrangement used in this paper, BeO had an optimum thickness around 15 centimeters.

2. The use of ^{233}U isotope in the cavity and/or in the driver region greatly improves the relative power of the cavity and reduces the amount of fuel needed for criticality in the driver region.

3. The placement of the pressure vessel outside of the driver region reflects neutrons back into the reactor and thereby increases reactivity to allow a reduction in mass in the driver which in turn improves the relative power produced in the cavity. For a given mass of fuel in cavity (1 kg) the external pressure vessel increased cavity power fractions to 0.21 for a 12.7 cm thick vessel from 0.16 for a 2.5 cm vessel.

4. The effect of hydrogen density on reactivity is approximately 1 percent $\Delta K/K$ over the range of interest.

REFERENCES

1. J. G. GALLAGHER and L. H. BOMAN, "The NERVA Technology Reactor for a Brayton Cycle Space Power Unit," Trans. Am. Nucl. Soc., 12, 417, (1969).

2. P. H. DUNDAS, "Induction Plasma Heating: Measurement of Gas Concentrations, Temperatures, and Stagnation Heads in a Binary Plasma System," NASA CR-1527 (1970).

3. J. C. BENNETT and B. V. JOHNSON, "Experimental Study of One and Two Component Low-Turbulence Confined Coaxial Flows," J910934-10, United Aircraft Research Laboratories (1971).

4. J. F. KUNZE, J. H. LOFTHOUSE, D. H. SUCKLING, and R. E. HYLAND, "Flow Mixing, Reactivity Effects in the Gas-Core Reactor," Trans. Am. Nucl. Soc., 14, 11 (1971).

5. J. W. POOLE and C. E. VOGEL, "Induction Plasma Nozzle Test," NASA CR-1765 (1971).

6. J. H. LOFTHOUSE and J. F. KUNZE, "Spherical Gas-Core Reactor Critical Experiment," IN-1443, NASA CR-72781, Idaho Nuclear Corp. (1971).

7. J. F. KUNZE, G. D. PINCOCK, and R. E. HYLAND, "Cavity Reactor Critical Experiments," Nucl. Appl., 6, 104 (1969).

8. G. D. PINCOCK and J. F. KUNZE, "Cavity Reactor Critical Experiment. Vol. IV-Waves and Control Methods," IN-1336, NASA CR-72550, Idaho Nuclear Corp. (1969).

9. C. BARBER, "A FORTRAN IV Two-Dimensional Discrete Angular Segmentation Transport Program," NASA TN D-3573 (1969).

10. R. G. RAGSDALE, "Relationship Between Engine Parameters and the Fuel Mass Contained in an Open-Cycle Gas-Core Reactor," Research on Uranium Plasmas and Their Technological Applications, NASA SP-236 (1971), p. 13.

11. A. F. KASCAK, "The Radiant Heat Flux Limit of Bypass Flow in a Uranium Plasma Rocket," Research on Uranium Plasmas and Their Technological Applications, NASA SP-236 (1971), p. 236.

12. H. C. HALLER, S. LIEBLEIN, and B. LINDOW, "Analyses and Evaluation of a Vapro Chamber Fin-Tube Radiator for high Power Rankine Cycles," NASA TN D-2836 (1965).

TABLE I. - NEUTRON ENERGY GROUP LEVELS

Group	ΔU (lethargy)	Lower energy
1	1.4	3.7 MEV
2	.5	2.2
3	.5	1.4
4	1.0	0.5
5	1.0	.18
6	1.0	67 KEV
7	1.0	25
8	2.0	3.4
9	2.0	454 eV
10	2.0	61
11	2.0	8.312
12	1.25	2.38
13	1.749	0.414
14	0.7275	.2
15	.5108	.12
16	0.4055	0.08
17	1.151	.025
18	1.621	.005
19	(2.0)	0

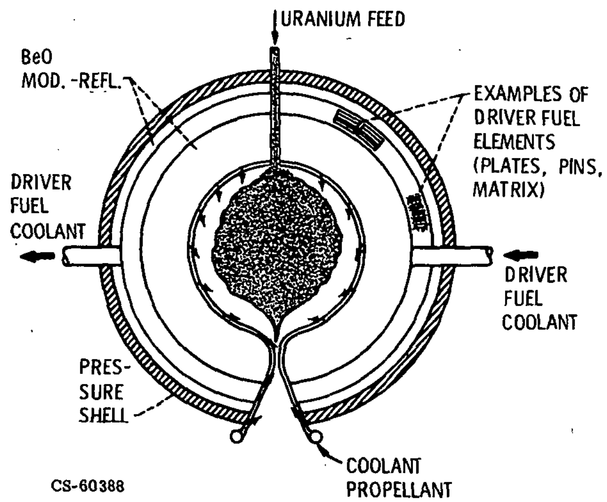
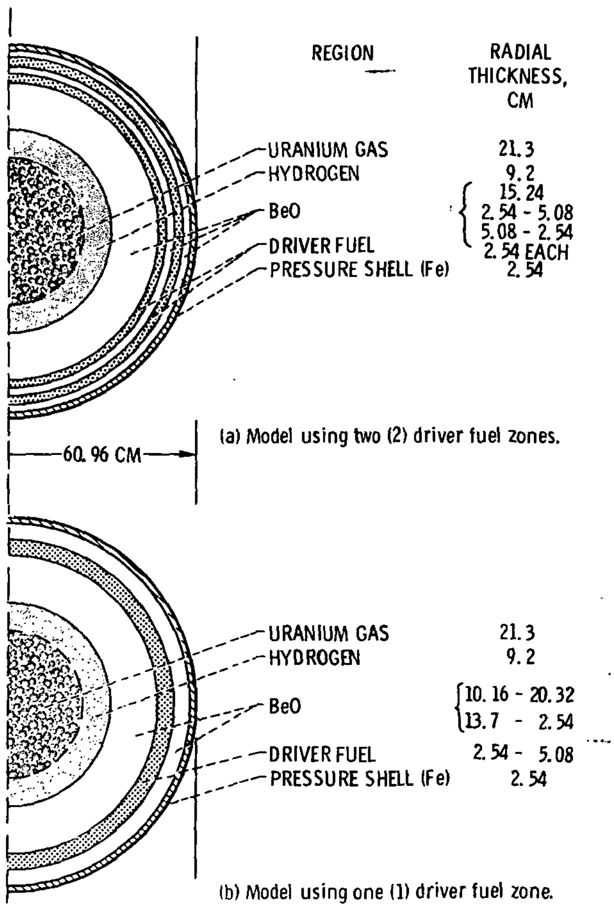


Figure 1. - Mini-cavity reactor concept for probe propulsion.



(a) Model using two (2) driver fuel zones.

(b) Model using one (1) driver fuel zone.

Figure 2. - Calculational models (spheres) for reactor.

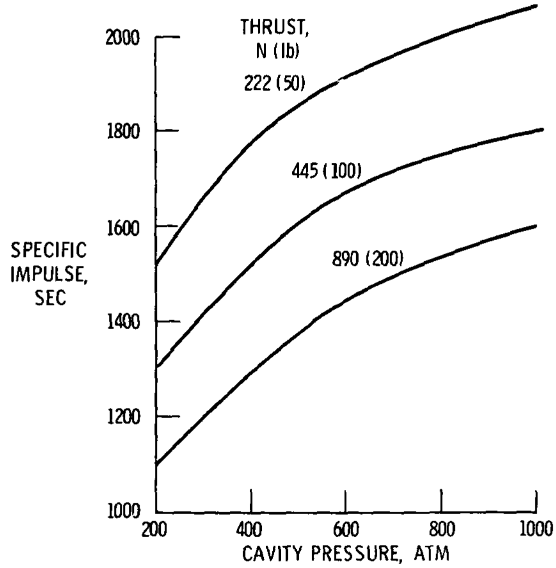


Figure 3. - Propulsion characteristics for mini-cavity concept. Cavity diameter, 0.61 meter; wall temperature, 1523° K.

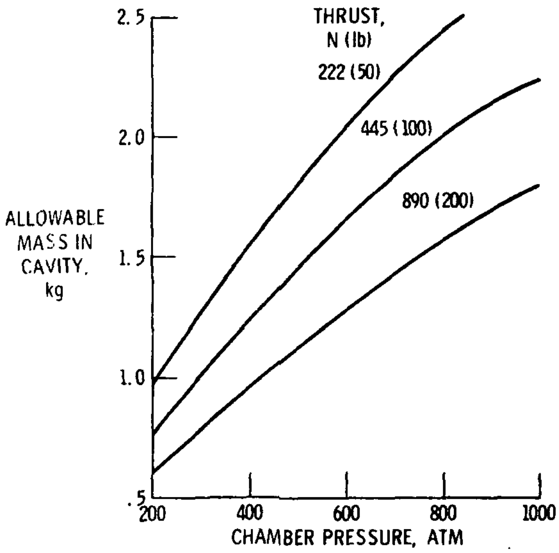


Figure 4. - Allowable uranium mass in cavity. Cavity diameter, 0.61 meter; fuel volume fraction, 0.30.

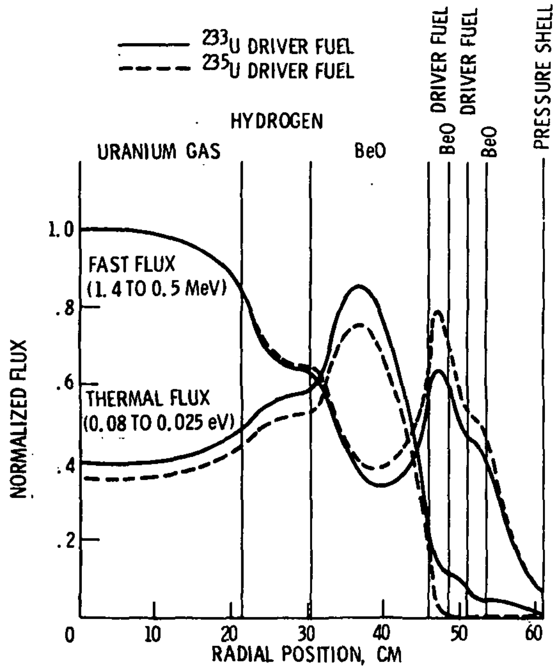


Figure 5. - Neutron flux for mini cavity reactor.

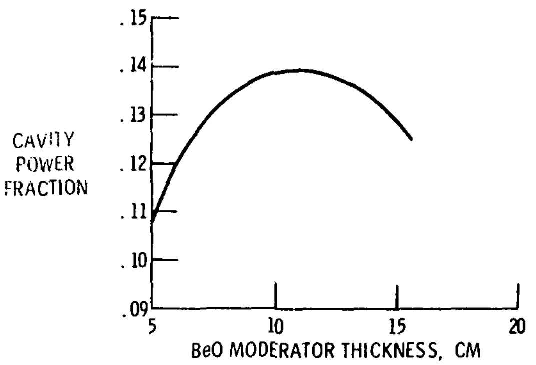


Figure 6. - Optimization of moderator thickness for mini-cavity.

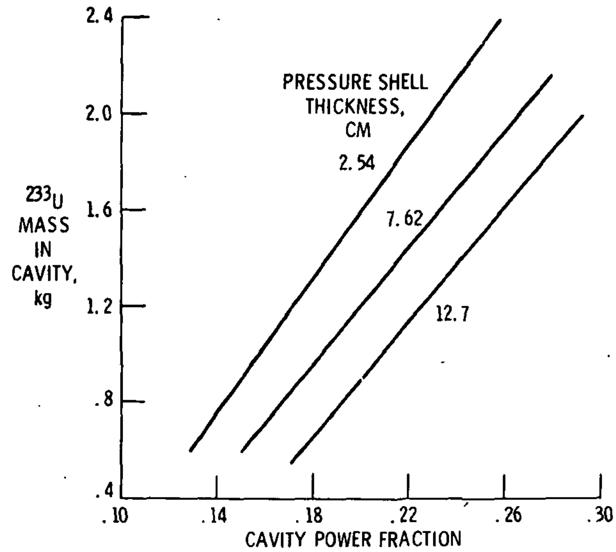


Figure 7. - Pressure shell effect on cavity power fraction ^{233}U fuel in both cavity and driver regions.